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THE EFFECT OF POST PANGEA SUBDUCTION ON GLOBAL MANTLE TOMOGRAPHY AND CONVECTION

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Abstract. There is an excellent correlation between tomographic patterns and global tectonics in the upper 200 km of the mantle. Below this depth there is little relationship with present tectonic provinces. Most of the power in the tomography is in the longest wavelengths (ℓ=1-3) with ℓ=2 generally dominant. This is quite different from expectations based on mantle convection models. The question then arises, what causes the long wavelength variations mapped by seismic techniques? We investigate the hypotheses that past locations of supercontinents and subduction may control temperature variations in the mantle. We look for correlations between Pangea and post-Pangeatic subduction and seismic velocity variations at various depths. The best correlations with time integrated slab locations occur near the base of the uppermantle, suggesting that slabs bottom out in the mesosphere. The Pangea hemisphere has a colder than average uppermantle, probably due to circum- and intra-Pangea subduction. Hotspots and ridges avoid regions cooled by subduction over the past 180 Ma. The presence of large continents at the surface and large areas of cold slab at depth explain the dominance of long wavelengths in the mantle's thermal structure, despite the high Rayleigh number.

Introduction

Tomographic studies of the mantle show abundant power in the longest wavelengths (Masters et al., 1982, Nakanishi and Anderson, 1982, Nataf et al., 1984, Tanimoto, 1990a, Su and Dziewonski, 1991, Zhang and Tanimoto, 1992). The depth of penetration of slabs is controversial but Anderson (1989) noted a correlation of fast transition zone velocities with post-Pangeatic subduction which he interpreted in terms of slab trapping at 650 km. Engebretson et al. (1990) noted a similarity between past slab positions and depth averaged lower mantle velocities and argued for deep slab penetration. They did not treat the uppermantle. Richards and Hager (1988) suggested that dead slabs are distributed throughout the lower mantle.

Previous studies noted correlations between the geoid, lower mantle and hotspots. The correlations are extremely strong at ℓ=2, but are weak or inconsistent at other wavelengths, including ℓ=1 for the hotspot-tomography correlation. The ℓ=2 hotspot-lower mantle-geoid correlation led Richards et al. (1988) to propose that hotspots are directly related to the thermal structure of the lower mantle. The absence of other correlations including ℓ=1, suggests that any relationship to the lower mantle is weak or indirect. The peak in the spectra of various geophysical parameters at ℓ=2 is also unexplained.

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Richards and Engebretson (1992) compared time integrated slab positions (0 - 180 Ma) with the average lower mantle seismic velocity and concluded that the "thermal load" of subducted slabs, distributed through the depth of the lower mantle, could explain the correlation. There is significant correlation (>90%) only for ℓ=2 and 3, very poor correlation for ℓ=4 and weak correlation for ℓ=1. They did not consider correlations with the uppermantle or with various shells in the lower mantle. Anderson (1989) noted a spatial correlation between regions of overridden oceanic lithosphere and high seismic velocities in the transition zone, consistent with slabs bottoming out in the uppermantle. If this is so, the connection of subduction and temperatures in the lower mantle would be indirect, e.g. thermally induced downwellings beneath regions cooled from above by cold, horizontal slabs, or lower mantle downwellings dictating current positions of continents and trenches.

Method

We infer the locations of subduction zones (slabs) over the past 180 Ma from paleoreconstruction maps (Scotese, 1990). Grid points (5° by 5°) were given a value of 1 or 0, depending on whether they included or did not include a trench, and expanded in spherical harmonics. Pangea was expanded into spherical harmonics in the same way. Figure 1 shows the amplitude spectra of these expansions. Note that most of the power is in degrees 1, 2 and 3. These are also the degrees that correlate best with the tomography.

The seismic tomographic models at all depths in the mantle were correlated with the time integrated slab locations and with Pangea. The correlations were performed for all degrees, from

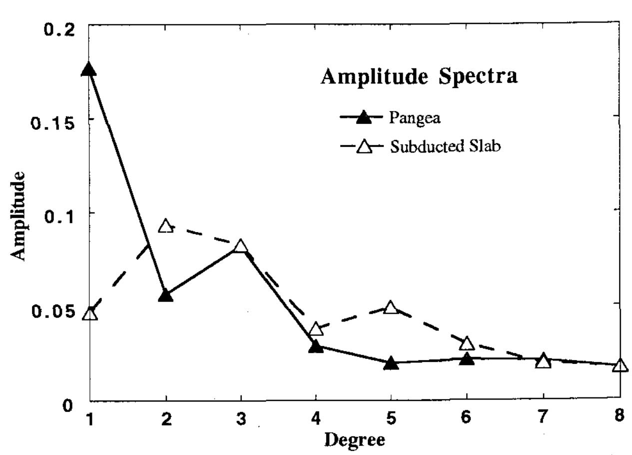

Fig. 1. Spectral amplitude vs. degree for spherical harmonic expansions (ℓ=1-8) of Pangea (solid line) and time-integrated (0-180 Ma) post-Pangea subduction (dashed line). We use fully normalized spherical harmonics (Richards et al., 1988).

TABLE 1. Correlation coefficients for the highest amplitude harmonics [ℓ=1 (Pangea) and ℓ=2 (Time-integrated slab positions)] with three seismic velocity models

Depth (km)	PANGEA			TIME-INTEGRATED SLAB		
		ℓ=1			ℓ=2	
	T	S&D	Iea	T	S&D	Iea
200	0.65	0.92	0.95	0.32	0.53	-0.01
300	0.81	0.89	0.91	0.70	0.76	0.21
400	0.85	0.92	0.64	0.75	0.78	0.69
500	0.89	0.95	0.27	0.76	0.78	0.78
800	-0.03	0.15	0.04	0.79	0.86	0.80
1000	0.03	-0.15	0.47	0.46	0.86	0.71
1500	-0.06	-0.63	0.05	0.30	0.75	0.47
2000	0.17	-0.62	-0.51	0.21	0.49	-0.01
2500	0.31	-0.30	-0.79	0.58	0.34	0.47
2800	0.22	0.11	-0.23	0.58	0.60	0.52

T=Tanimoto S&D=Su and Dziewonski Iea=Inoue et al. Underlined correlations are of > 90% statistical significance. Values are interpolated from the midpoints of the tomographic shells

ℓ=1 to 6. Tanimoto (1990a) divided the mantle into 11 shells and inverted for the spherical harmonic coefficients of seismic velocity. We interpolated Inoue et al's (1990) and Su and Dziewonski's (1991) models to the same depths. The spherical harmonic coefficients (ℓ=1 to 6) of the subducted slab were correlated with those for the seismic velocity distribution in each shell for each of the three seismic tomographic models. Approximate statistical significance curves (Eckhardt, 1984) indicate the extent to which particular correlations can be believed. The correlation is considered significant when the spherical harmonic degree has high amplitude coefficients, the significance level of the correlation is above 90%, and the correlation is consistent for two or three tomographic studies. Most of the tomographic power is in degrees 1 to 3 (Nakanishi and Anderson, 1983, Tanimoto, 1990a). Some of the results are given in Table 1. Correlations are poor or inconsistent for untabulated degrees.

Correlations

No reason has been given for the dominance of the ℓ=1-3 components in mantle tomographic studies. The hotspots spectrum, a possible measure of the thermal state of the mantle, is dominated by ℓ=1 and 2 but only ℓ=2 correlates with lower mantle tomography (Kedar et al, 1992). It is likely that the power in mantle convection is also dominated by low orders, although such is not the expection based on convection modeling (Glatzmaier et al., 1990).

Pangea was a pole-to-pole continent that covered most of one hemisphere. The amplitude spectrum shows that most of the power is in ℓ=1 with a minor peak at ℓ=3 (Figure 1). On a map view there are peaks over Africa and Asia and an anti-Pangea peak on the East Pacific Rise. The anti-Pangea region covers the Pacific and NE Indian Ocean, regions which have extremely low uppermantle seismic velocities. There is an excellent correlation at ℓ=1 between Pangea and uppermantle shear velocities. The sign of the correlation indicates that the Pangea hemisphere is fast. The Pacific Ocean long-wavelength uppermantle velocity anomaly is slower than average. Circum- and intra-Pangea subduction during assembly of the supercontinent may be responsible. It appears that insulation of the uppermantle by the supercontinent of Pangea (Anderson, 1989) is less important than subduction cooling caused by closure of ocean basins in the vicinity of Tethys and Eurasia, and subduction around the southern periphery of Gondwana, at least at ℓ=1. When Pangea broke up, the continental fragments moved radially away, overriding oceanic lithosphere in a band around the Pacific. Thus the overridden oceanic slab has a strong C_{22} term. This corresponds to a polar strip that contains most of the world's large geoid lows and continental shields (Anderson, 1989). Thus, in principle, we have phenomena, supercontinent assembly and breakup, that could pump power into the ℓ=1-3 components of mantle convection.

The time-integrated position of subducted slabs (0-180 Ma) exhibits peaks at ℓ=2 and 3 (Figure 1), just where most of the tomographic power is. The corresponding map (Figure 2) shows a broad ring around the Pacific under the Americas, E Asia, Australia, SE Asia, India, and the W Atlantic. These areas have fast seismic velocities in the transition region (Tanimoto, 1990a). The non-slab areas are Pangea and most of the Pacific and Indian Ocean basins.

There is much debate about the fate of the subducted slab. We know the geographic regions where subduction has occurred since the break-up of Pangea, but we don't know at what depth the slabs bottom out. Since the thermal assimilation time of cold lithopheric slabs is large we should be able to find them by their effects on seismic velocities. At ℓ=2 there is excellent correlation between integrated slab positions and the uppermantle, the transition region, and the top of the lower mantle (Table 1). There is very poor correlation with the rest of the mantle. The best and most consistent correlations are with fast mantle (cold) and subducted slab between depths of 300 and 800 km. The half-width of the radial resolution kernal is about 300 km (Tanimoto, 1990a) so all we can really say is that the peak of the correlation is near 550 km depth. Su and Dziewonski

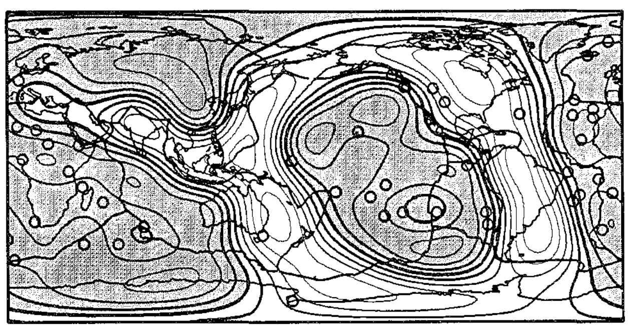

Fig. 2. Map of oceanic lithosphere which has been overridden by continents since the breakup of Pangea, 0-180 Ma, expanded to degree and order 8. The dark areas include Pangea and the parts of the Pacific which have not been overridden by continents. Plate boundaries and hotspots are also shown. Note that most ridges and hotspots are in the non-slab regions. The white band extending across the Americas to E. Asia and Australia correlates with high seismic velocities centered in the transition zone in the whole mantle model of Tanimoto (1990a).

(1991) use a low-order Legendre polynomial to describe the radial variation and this tends to smooth the radial structure. This may explain the broad correlation (Table 1) of their model. Their ℓ=2 correlation, however, is centered near the same depth as the others (600 - 900 km). The sense of the correlation is that fast (cold) mantle correlates with regions containing subducted lithosphere. The seismic models do not show a consistent correlation with the subducted slab at ℓ=3; Inoue et al. (1990) have a positive but localized correlation near the top of the lower mantle and Su and Dziewonski (1991) have a positive correlation at the base of the mantle. There are no consistent correlations for ℓ=4 and 5. For ℓ=6 there are some significant correlations in the transition region and top of the lower mantle.

In summary, we see a good correlation between predicted slab locations and fast seismic velocities in the transition region of the mantle, which degrades rapidly below the uppermantle. The main harmonic of the Pangea expansion, ℓ=1, has the most significant correlation with uppermantle velocities, the Pangea hemisphere having faster velocities than the Pacific hemisphere. There are no consistent correlations for ℓ>3 but the uppermantle correlations are generally better than lower mantle correlations for ℓ=4 to 6. The main harmonic of the integrated slab expansion, ℓ=2, has maximum correlation in the transition region. There is good agreement between tomographic studies of the uppermantle for long wavelengths. We therefore feel that our correlations are robust. On the other hand, resolution begins to get poor at greater depth and there is the danger that shallow anomalies get smeared into the deeper part of the mantle. Radial smearing is probably most pronounced for the Dziewonski (1984) and Su and Dziewonski (1991) models.

Correlation of Hotspots with past-slab positions

Hotspots concentrate under the Pacific and African plates, regions where the lower mantle tends to have low seismic velocities. Using the hotspot list of Richards et al. (1988), we obtain strong negative correlations between the 0-180 Ma slab locations and hotspots (Figure 3). This suggests hotspots do not originate in mantle that has been cooled or blocked by slab. We also note that oceanic ridges mainly occur in regions not cooled by subduction (Figure 2). Hotspots, ridges, and low seismic velocities are all manifestations of hot mantle. Such regions appear not to have been recently cooled by subduction. Our results suggest that hotspots, or hot areas, may only be hot by comparison. They may be "normal" mantle that has not been cooled by subduction. Upwellings may be fixed in position by irregularities in flat lying slabs or by topography at the base of the uppermantle caused by lower mantle convection. Although midocean ridges are mobile and are generally regarded as passive, they appear not to form, survive or migrate over mantle that is underlain by slab, at least in the last 180 Ma.

Previous Work

Richards and Engebretson (1992, hereafter R & E) suggest that a direct relationship exists between large-scale thermal heterogeneity in the lower mantle and subduction during the Cenozoic and Mesozoic. Because of the good

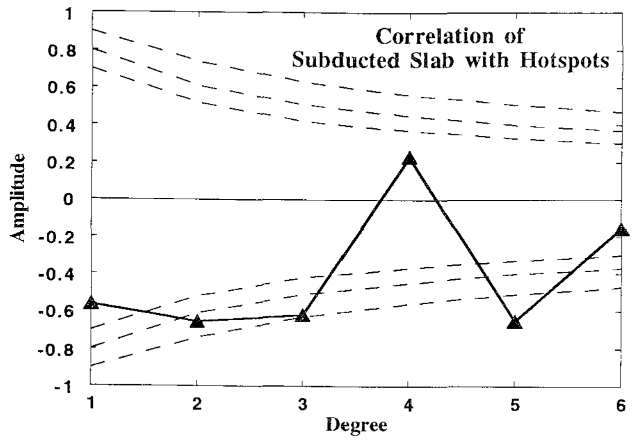

Fig. 3. Correlation coefficients between hotspots and time-integrated subduction (0-180 Ma). The dashed lines give significance levels from 0.7 to 0.9. There is good correlation at degrees 3 and 5 and fair correlation at ℓ=2. Overall, hotspots tend to be where subduction has not cooled the mantle. Oceanic ridges also tend to avoid previous subduction areas.

correlation between subduction and uppermost lower mantle and transition zone seismic velocities, however, we feel that the relationship is indirect. Cold slabs in the transition zone may cool the top of the lower mantle. R & E used an early tomographic study of Dziewonski (1984) and restricted their correlations to a radially averaged lower mantle. They obtained significant (>90%) correlations only for ℓ=2 and 3. In contrast, we use individual shells of more recent models and, in particular, treat the uppermantle and mesosphere, regions ignored by R & E. When we look at individual shells of the lower mantle we sometimes find good correlations at either the top or the bottom but not with the whole lower mantle. The tomographic maps and spectra at 400-670 km and 2630-2891 km (Tanimoto, 1988) look similar, but the large scale pattern is shifted (Tanimoto 1990b).

Discussion

We conclude that variations in uppermantle temperatures, as manifested in tomographic and hotspot patterns, are strongly influenced by supercontinent assembly and dispersal. The large scale pattern of convection inferred from tomography and the geoid, unexpected for high Rayleigh number convection, is thus explained.

The most efficient mechanism for cooling the mantle is by subduction of cold oceanic lithosphere. Our results suggest that subducted or overridden oceanic lithosphere plays a major role in causing long wavelength temperature variations in the uppermantle, particularly in the transition region. There is a weak correlation with structure at the top of the lower mantle, but this region and the mesosphere are within the resolution length of the tomography. We suggest that slabs are confined to the uppermantle but that they influence the seismic velocity of the lower mantle. There is no correlation of past slab positions with the bulk of the lower mantle. The correlation becomes stronger at the base of the mantle for some models.

Although previous correlation between slabs, hotspots, geoid and lower mantle tomography have been used to argue for whole mantle convection, and a deep origin for mantle plumes, we should point out that some correlation between upper and lower mantle should exist even for layered convection models. If the lower mantle has high viscosity, its long wavelength pattern may be transferred to the uppermantle by thermal and topographic coupling. Continents will probably tend to drift away from lower mantle upwellings, bringing them and their associated subduction zones over the downwelling parts of the lower mantle. In the opposite sense, cold slab lying at the top of the lower mantle will cool it and may trigger cold downwellings. Because conduction is a slow process and the lower mantle presumably has a high-viscosity, the induced downwellings may only have penetrated partway into the lower mantle.

Tanimoto (1990b) and Su and Dziewonski (1991) have shown that the 650 km discontinuity is the boundary between different styles of lateral variations and, presumably, of convection as well. The uppermantle has a different spectrum and pattern of velocity variations than the lower mantle, and the change sets in near the discontinuity. This is consistant with weakly coupled layered convection.

We speculate that the temperature variations and the pattern of convection in both the uppermantle and lower mantle are controlled by present subduction zones, and by past loci of convergence (and therefore, the present locations of cold slab at the base of the uppermantle), and by the present and past locations of continents. Hot upwelling in the lower mantle can also affect uppermantle convection even if there is no transfer of material.

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